Weak decay of heavy hadrons based on the dynamical supersymmetry of the anti s quark and the ud diquark

ELPH 研究会 C033「ハドロン分光に迫る反応と構造の物理」

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December 7, 2022

H. Akiyama, T. Amano, D. Jido, S. Leupold, In preparation

Topics

Symmetry for $\bar{s}$ quark and ud diquark

- Diquark: Composite particle of two quarks.
- Investigate the properties of diquarks with symmetry.
- We focus on "Good diquark"(spin-0, color $\bar{\mathbf{3}}$)

Dynamical supersymmetry

	ud	$\bar{s}$	
Mass	$\sim 500\text{MeV?}$	$\sim 500\text{MeV}$	→Similar mass
Color	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	→Same color
Spin	0	$\pm\frac{1}{2}$	

$$\Rightarrow \text{V(3) symmetry:} \hat{\Psi} = \begin{pmatrix} \bar{s}_\uparrow \\ \bar{s}_\downarrow \\ ud \end{pmatrix}.$$

cf.)SU(3) flavor symmetry

T. Amano, D. Jido, Prog. Theor. Phys. 2019, 093D02 (2019).
H. Miyazawa, Phys. Rev. 170, 1586 (1968)

Symmetry for $\bar{s}$ quark and ud diquark

Heavy hadron masses

	Hadron			Mass[MeV]	
spin	0	1	$\frac{1}{2}$		
$\hat{\Psi}b$	$(\bar{B}_s^0$	$\bar{B}_s^{*0}$	$\Lambda_b^0)$	(5367, 5415,5620)	Symmetry breaking is
	$\bar{s}b$	$\bar{s}b$	udb		~5%
$\hat{\Psi}c$	$(D_s^+$	D_s^{*+}	$\Lambda_c^+)$	(1968, 2112,2286)	Symmetry breaking is
	$\bar{s}c$	$\bar{s}c$	udc		~15%
※ $\hat{\Psi}s$	$(\eta_s^0$	ϕ^0	$\Lambda^0)$	(?, 1019,1116)	
	$\bar{s}s$	$\bar{s}s$	uds		

※ Strictly, $\hat{\Psi}\Psi$ multiplet

$$|\eta_s\rangle \equiv |s\bar{s}_{J^P=0^-}\rangle = -\sqrt{\frac{2}{3}}\,|\eta\rangle + \sqrt{\frac{1}{3}}\,|\eta'\rangle$$

$$|\eta\rangle = \frac{1}{\sqrt{6}}(|u\bar{u}\rangle + |d\bar{d}\rangle) - \frac{2}{\sqrt{6}}\,|s\bar{s}\rangle\,, \quad |\eta'\rangle = \frac{1}{\sqrt{3}}(|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle)$$

T. Amano, D. Jido, Prog. Theor. Phys. 2019, 093D02 (2019).

Weak decay of hadrons

- We would like to investigate the symmetry of the wavefunction.

$\Rightarrow$ Investigate weak decay of hadrons.

Weak decay of bottom hadrons

- Nonleptonic decay: $\hat{\Psi}b \to P^- \hat{\Psi}c, \quad P^- = \pi^-, K^-, \rho^-, \cdots$
- Semileptonic decay: $\hat{\Psi}b \to \ell^- \bar{\nu}_\ell \hat{\Psi}c$

Ex. Pionic decay of bottom hadrons

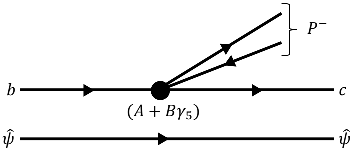
- $\Lambda_b \to \pi^- \Lambda_c^+$ ($J^P = \frac{1}{2}^+$ baryon $\to J^P = \frac{1}{2}^+$ baryon)
- $\bar{B}_s^0 \to \pi^- D_s^+$ ($J^P = 0^-$ meson $\to J^P = 0^-$ meson)
- $\bar{B}_s^0 \to \pi^- D_s^{*+}$ ($J^P = 0^-$ meson $\to J^P = 1^-$ meson)

Weak decay of hadrons with V(3) symmetry

- Amplitude(Phenomenology): $\mathcal{M} = \mathcal{M}_h^\mu \mathcal{M}_{P\mu}$
- $\mathcal{M}_{P\mu}$: Weak current ($\partial_\mu \phi_\pi$:pionic decay, ρ_μ:ρmesonic decay)
- $\mathcal{M}_h^\mu = \bar{u}_c^{(\alpha)} \gamma^\mu (A + B\gamma_5) u_b^{(\beta)}$: Hadronic current
- Decay rate: $\Gamma = \frac{(2\pi)^4}{2M_{\hat{\Psi}b}} \int d\Phi_n \sum_{\text{spin}} (\mathcal{M}_h^{\mu\dagger} \mathcal{M}_h^\nu)(\mathcal{M}_{P\mu}^\dagger \mathcal{M}_{P\nu})$

Assumption

- $\hat{\Psi}$ is a spectator$\rightarrow$ $\mathcal{M}_h^\mu$ is given by the quark transition alone.
- V(3) symmetry $\rightarrow$ A, B is common for each decay mode



T. Amano, D. Jido, S. Leupold, Phys. RevD.105.L051504(2022)

Weak decay of hadrons with V(3) symmetry

General decay rate

- $\Gamma_{\bar{B}_s^0 \to D_s^+ P^-} = K_{Ap}|A|^2$
- $\Gamma_{\bar{B}_s^0 \to D_s^{*+} P^-} = K_{Av}|A|^2 + K_{Bv}|B|^2 + K_{ABv}|A||B|\cos(\arg A - \arg B)$
- $\Gamma_{\Lambda_b^0 \to \Lambda_c^+ P^-} = K_{Ab}|A|^2 + K_{Bb}|B|^2 + K_{ABb}|A||B|\cos(\arg A - \arg B)$

K depend on only hadron masses.
$K_{AB} \neq 0$ only for semileptonic decay with massive lepton.

For $K_{AB} = 0$

- $\Gamma_{\Lambda_b^0 \to \Lambda_c^+ P^-} = C_p \Gamma_{\bar{B}_s^0 \to D_s^+ P^-} + C_v \Gamma_{\bar{B}_s^0 \to D_s^{*+} P^-}$: Corrected sum rule
- $\Gamma_{\bar{B}_s^0 \to D_s^+ P^-}, \Gamma_{\bar{B}_s^0 \to D_s^+ P^-} \xrightarrow{\text{verify}} |A|, |B|$

Weak decay of hadrons with V(3) symmetry

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- $\Gamma_{\Lambda_b^0 \to \Lambda_c^+ P^-} = K_{Ab}|A|^2 + K_{Bb}|B|^2 + K_{ABb}|A||B|\cos(\arg A - \arg B)$

K depend on only hadron masses.

$K_{AB} \neq 0$ only for semileptonic decay with massive lepton.

For $K_{AB} \neq 0$ i.e. semileptonic decay with massive lepton

- A, B are real under CP symmetry.$\Rightarrow \cos(\arg A - \arg B) = \pm 1$
- $\Gamma_{\bar{B}_s^0 \to D_s^+ P^-}, \Gamma_{\bar{B}_s^0 \to D_s^+ P^-} \xrightarrow{\text{verify}} |A|, |B| \xrightarrow{\text{verify}} \Gamma_{\Lambda_b^0 \to \Lambda_c^+ P^-}$

Decay parameter of baryon

- We can extract the absolute value of effective coupling constants $|A|, |B|$ from meson decay rates.
- We can calculate the baryon decay asymmetry parameter α using $|A|, |B|$.

$$\alpha = \cos(\arg A - \arg B)\alpha\left(\left|\frac{B}{A}\right|\right)$$

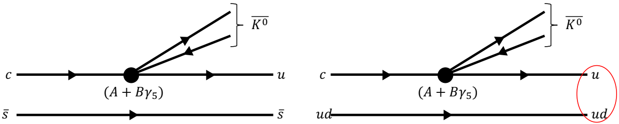
- We set A, B are real.*

*A.I. Vainshtein, V. I. Zakharov, M.A. Shifman, ZhEFT, 72 (1977).

Result(Decay rate)

Table: Decay rate of charm hadrons[s^{-1}]. For muonic decay, the first and second value is $\cos(\arg A - \arg B) = -1, +1$.

	Baryon decay rate	
	Exp.	Calc.
$\hat{\Psi}b \to \hat{\Psi}c\pi^- \ \times 10^9$[s^{-1}]	3.33±0.27	$3.38^{+0.37}_{-0.31}$
$\hat{\Psi}c \to \hat{\Psi}s\pi^+ \ \times 10^{10}$[s^{-1}]	6.45±0.35	21.0±1.4
$\hat{\Psi}c \to \hat{\Psi}u\bar{K}^0 \ \times 10^{10}$[s^{-1}]	7.89±0.04	28.7±5.0
$\hat{\Psi}c \to \hat{\Psi}se^+\nu_e \ \times 10^{11}$[s^{-1}]	1.79±0.20	1.58±0.09
$\hat{\Psi}c \to \hat{\Psi}s\mu^+\nu_\mu \ \times 10^{11}$[s^{-1}]	1.74±0.25	1.22±0.27, 1.67±0.31



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Result(Decay parameter)

Table: Baryon decay asymmetry parameter. Values in brakets are theoretical. $\delta \equiv \cos(\arg A - \arg B)$.

	α	
	Exp.	Calc.
$\Lambda_c \to \Lambda\pi^+$	-0.84 ± 0.09	-0.851 ± 0.011
$\Lambda_c \to \Lambda e^+\nu_e$	-0.86 ± 0.04	-0.784 ± 0.006
$\Lambda_c \to \Lambda\mu^+\nu_\mu(\delta = -1)$	-0.86 ± 0.04	-0.857 ± 0.02
$\Lambda_c \to \Lambda\mu^+\nu_\mu(\delta = +1)$	-0.86 ± 0.04	0.692 ± 0.003

Result(Effective coupling constants for semileptonic decay)

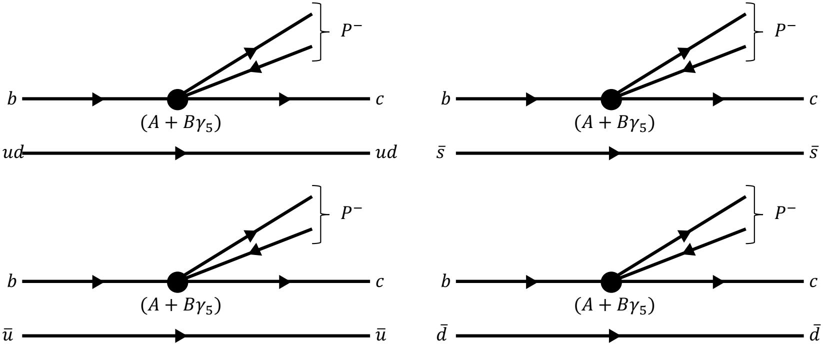
- In semileptonic decay, the hadronic current does not depend on the lepton generation, since there is no correction for strong interactions.
- $|B|$ differs between electron and muon.

Table: The absolute values of effective coupling constans [10^{-12}MeV^{-2}].$\delta \equiv \cos(\arg A - \arg B)$

	$\|A\|$	$\|B\|$
$\hat{\Psi}c \to \hat{\Psi}se^+\nu_e$	7.44±0.12	7.52±0.28
$\hat{\Psi}c \to \hat{\Psi}s\mu^+\nu_\mu(\delta = -1)$	7.88±0.75	4.64±0.97
$\hat{\Psi}c \to \hat{\Psi}s\mu^+\nu_\mu(\delta = +1)$	7.88±0.75	10.0±1.0

Difference with heavy quark symmetry

- If heavy quark symmetry holds, replacing $\hat{\Psi}$ with $\bar{u}, \bar{d}$ as a spectator is not expected to change the amplitude.



$\rightarrow$ Determin $|A|, |B|$from the decay of each meson, and calculate the decay rate of the baryon

Difference with heavy quark symmetry

- If heavy quark symmetry holds, replacing $\hat{\Psi}$ with $\bar{u}, \bar{d}$ as a spectator is not expected to change the amplitude.
- V(3) symmetry is better than heavy quark symmetry

Table: The absolute values of effective coupling constans $[10^{-12}\text{MeV}^{-2}]$ and decay rates of bottom hadrons, for pionic decay $[10^{9}\text{s}^{-1}]$, kaonic decay $[10^{8}\text{s}^{-1}]$.

	Decay rate	$\lvert A \rvert$	$\lvert B \rvert$
$\Lambda_b^0 \to \Lambda_c^+ \pi^-$	3.33±0.27(Exp.)		
$(\bar{s})\bar{B}_s^0 \to D_s^{+(*)} \pi^-$	$3.38^{+0.37}_{-0.31}$	2.54±0.06	$2.10^{+0.28}_{-0.22}$
$(\bar{u})B^- \to D^{0(*)} \pi^-$	6.53±0.13	3.10±0.04	3.37±0.05
$(\bar{d})B^0 \to D^{+(*)} \pi^-$	3.75±0.11	2.36±0.04	2.55±0.06
$\Lambda_b^0 \to \Lambda_c^+ K^-$	2.42±0.19(Exp.)		
$(\bar{s})\bar{B}_s^0 \to D_s^{+(*)} K^-$	$2.47^{+0.30}_{-0.25}$	7.04±0.19	$5.64^{+0.855}_{-0.684}$
$(\bar{u})B^- \to D^{0(*)} K^-$	2.57±0.11	9.11±0.20	1.05±0.14
$(\bar{d})B^0 \to D^{+(*)} K^-$	2.98±0.12	6.79±0.13	7.22±0.26

Summery

Model

- Consider the symmetry for $\bar{s}$ quark and ud diquark.
- Investigate the weak decay of heavy hadrons: $\hat{\Psi}b \to P\hat{\Psi}c$,$\hat{\Psi}c \to P\hat{\Psi}s$.
- $\hat{\Psi}$ is a spectator.

Result

- Reproduces experimental values of baryon decay rate and decay paremeter well.
- Cannot reproduced well the baryon decay rate of charm hadrons for pionic decay.$\to$ Final state interaction? diquark picture is bad in Λ?
- Amplitude of semileptonic decay depends on the lepton generation. $\to q^2$ dependence?
- V(3) symmetry is better than heavy quark symmetry.

Outlook

Next

- Calculate the decay rate in micoscopic way.
- Verify the origin of symmetry breaking for pionic decay of charm hadron.
- Investigate the q^2 dependence of amplitude.

Afterward

- Investigate the symmetry of the wavefunction in production process($e^+e^- \to \hat{\Psi}b\overline{\hat{\Psi}b}$)
- V(3) symmetry in heavy ion collision production.
  - Restore the chiral symmetry in high temperature system.
  - Investigate the origin of diquark mass

Back up slide

Result(Effective coupling constants for semileptonic decay)

- In semileptonic decay, the hadronic current does not depend on the lepton generation, since there is no correction for strong interactions.
- $|B|$ differs between electron and muon.$\rightarrow$ $q^2 = (p_\ell + p_\nu)^2$ dependence of A, B?

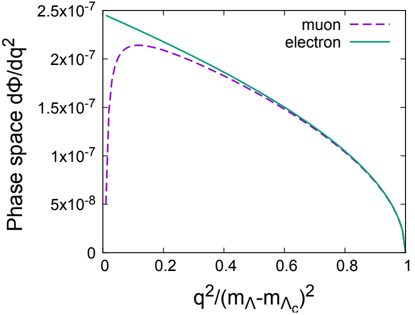


Figure: q^2 dependence of phase space. Peak positions are $\frac{q^2}{(m_\Lambda - m_{\Lambda_c})^2} = 5.83 \times 10^{-4}, 0.117$ in electronic decay and muonic decay, respectively.

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